Art. XVI.—*The Tasmanian Tektite—Darwin Glass.*

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(With Plate XIII.)

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Contents.

I.—Introduction.

Considerable interest has been excited for many years past through the scientific world in the small bodies known as Tektites, the origin of which is still a mystery. Quite an extensive literature already exists dealing with the Moldavites of the Moldau River area, the Billitonites of the Netherlands East Indies, the Australites of the Commonwealth, and the Schonite of Scandinavia.

The remarkable variety of tektite known as Darwin Glass, has, as yet, hardly attracted the attention which its importance seems to the writers to deserve. Darwin Glass, so far, has been received only from the area of the Jukes-Darwin mining field. This area is situated to the east of Macquarie Harbour on the West Coast of Tasmania, and commences at a point about 12 miles south of the Mount Lyell Mine. A full account of its

original discovery through Mr. V. Bruscoe, M. Donohue and Mr. Hartwell Conder, M.A., Assoc.R.S.M., is given in the original paper describing this glass by Professor Franz Suess (1). In it he quotes from a detailed letter describing the occurrence by Loftus Hills and Twelvetrees. This is reviewed in still more detail by Dr. Loftus Hills (2).

One of the writers, Professor Sir Edgeworth David, recently was so much impressed with the importance of this discovery that he made a special visit to the principal locality and had the good fortune to be accompanied by Mr. Hartwell Conder, the engineer who was chiefly responsible for bringing the matter before the scientific world. He desires specially to acknowledge the invaluable help and advice of Mr. Conder, and the generous assistance given him by Mr. R. M. Murray, General Manager of the Mount Lyell Mine, Mr. H. J. Clarke, Engineer of Works, Mr. D. Lumsden, Secretary of the Mount Lyell Company, Sir John Grice, Chairman of Directors of the Emu Bay Railway Company, and to the Tasmanian Government for travelling facilities. Lastly he is specially indebted to Dr. Loftus Hills for details in regard to mode of occurrence, etc., of the Darwin Glass, suggested by the latter's extensive personal local knowledge.

II.—Bibliography.

Reference has already been given to the two and only papers hitherto dealing with the subject of Darwin Glass.

In Professor Suess's paper the Darwin Glass, as it was originally named by the late W. H. Twelvetrees, former Government Geologist of Tasmania, is named Queenstownite—Queenstown being the largest settlement in its vicinity. Professor Suess would have named it Tasmanite, but for the fact that the term is already bespoken for the spore-bearing oil shale of the Latrobe area in Tasmania. The term Darwinite is also already appropriated to a mineral. It is proposed in this paper to adhere to Mr. Twelvetrees' original name of Darwin Glass. An objection to Queenstownite is that there are at least four towns within the British Empire of that name. Professor Suess has given such an excellent description of the Darwin Glass, together with chemical analyses, that we have little to add to his classic paper. Nevertheless some new observations have come to light which seem worth recording. Dr. Loftus Hills has well summarised all that was known about Darwin Glass up to the year 1915. His account should be read in conjunction with his work on the Jukes-Darwin mining field, forming Bulletin No. 16 of the Geological Survey of Tasmania.

III.—Mode of Occurrence.

The area where Darwin Glass seems to be most abundant is at the Ten Mile on the spur of Mount Darwin, trending down to the railway cutting at ten miles up from Kelly's Basin on Macquarie
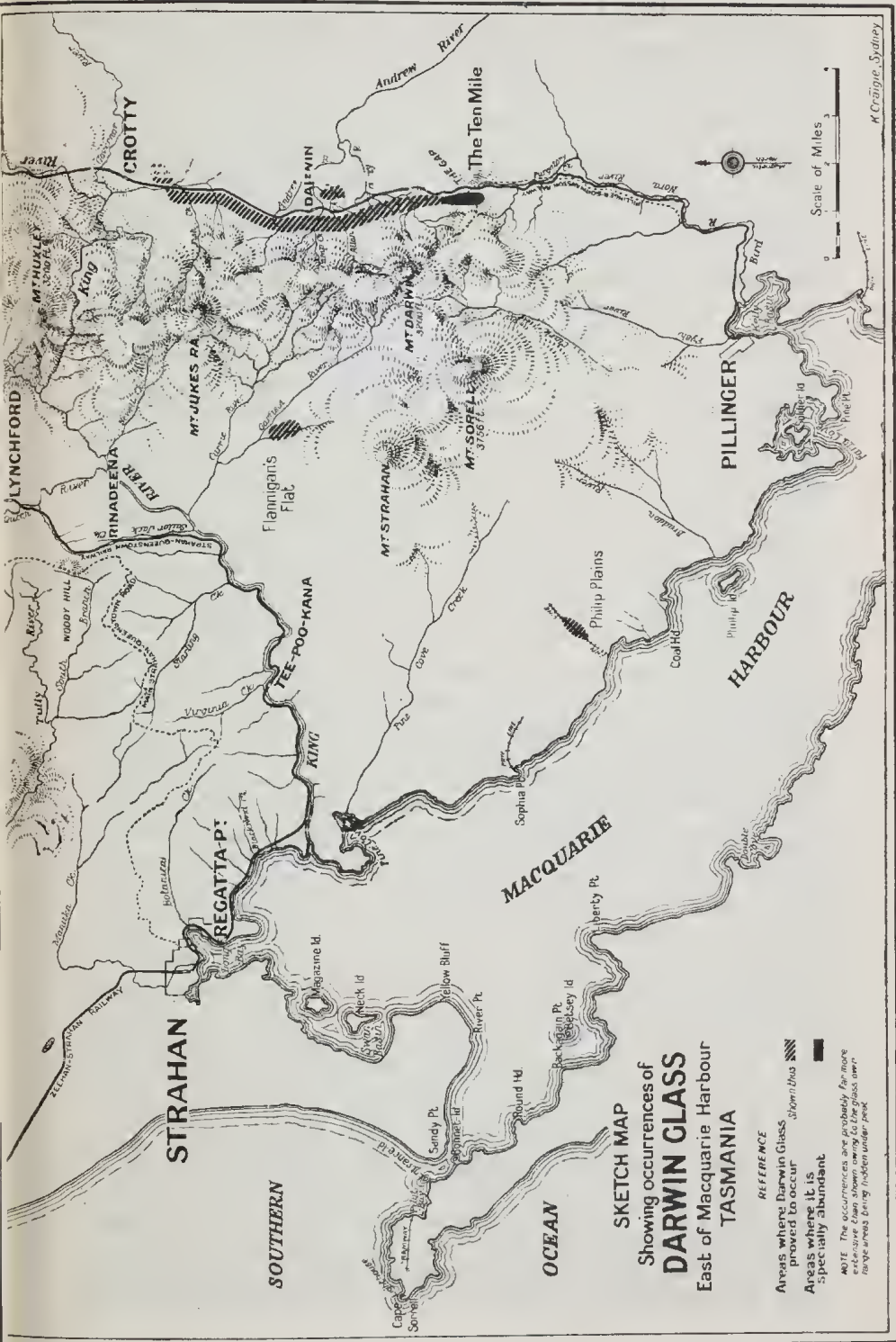
SKETCH MAP
Showing occurrences of
DARWIN GLASS
East of Macquarie Harbour
TASMANIA

REFERENCE

Areas where Darwin Glass
proved to occur

Areas where it is
specially abundant.

*NOTE. The occurrences are probably far more
extensive than shown owing to the glass over
large areas being hidden under peat.*

Fig. 1.

Harbour northwards, on the North Lyell Railway. The Darwin Glass is abundantly found in the cutting itself, and up the hill slope to a height of about 1300 feet above sea level. Strange to say, above the level of 1300 feet, the Darwin Glass has nowhere been met with, either on Mounts Darwin, Jukes, or Sorell. An ingenious explanation of the restriction in altitude of the occurrence of the Darwin Glass has been offered by Mr. Hartwell Conder. It is well known that this West Coast of Tasmania was heavily glaciated in Pleistocene time, and Mounts Darwin, Jukes, Sorell, and adjacent areas, show abundant evidence of the snow fields and glaciers having come down to within about 1000 feet of sea level. Indeed, during the maximum glaciation in early Pleistocene time, the glaciers in the Henty area came to within 200 feet or less of sea level. Conder assumes that, on the theory that the Darwin Glass was of meteoritic origin, as will appear most probable in the sequel, the hailstorm of small meteorites fell uniformly over the whole area of Mount Darwin for some twelve miles north of the Ten Mile, about ten miles east of the railway line, and four miles west, on the western slopes of Mount Sorell, and at Flanagan's Flat, west of Mount Darwin. In the case, however, of portion of this area which may have still been capped with ice and névé, the meteorites would become lodged in the ice, and would be gradually transported by it towards the ice margin, which at that particular time Conder argues would, on this hypothesis, be about at the top limit at which Darwin Glass is now found, namely 1300 feet above sea level.

If this view is correct, later investigation should show that the top limit of occurrence of the Darwin Glass on the western side of Mounts Darwin and Sorell is probably a little lower than that on the eastern, as the fall of the ice was chiefly westwards. This is an interesting point for detailed future investigation. We verified the statement that the Darwin Glass did not occur above the 1300 feet contour on Mount Darwin, and Conder, as well as Dr. Loftus Hills, is convinced that the glass is really absent from the higher levels. For example Donohue was much engaged in prospecting the higher levels of Darwin in search of gold, and although he was constantly on the look-out for Darwin Glass, with which he was particularly familiar, he never discovered a single specimen at the higher altitudes. At the Ten Mile the Darwin Glass occurs mostly immediately under a superficial covering of peat, which mostly forms the surface of this part of the hill slope. The peat is from 9 inches to about 18 inches in thickness. Immediately under the peat is fine rock rubble, from an eighth of an inch up to over an inch in diameter, the layer being from two to four inches in thickness, formed of pinkish sandstone or quartzite. This belongs to the West Coast Conglomerate Series of Silurian age. The Darwin Glass does not occur in the peat, which is of post-glacial origin, but only in the top two or three inches of rock rubble. Underneath the rubble is a foot or so of very fine pinkish grey sand. In places this sand thins out and

even the rock rubble also, in which case the Darwin Glass is found resting on a surface of pink quartzite. In places the covering of peat has been removed by erosion, so that the Darwin Glass is exposed at the surface. It can most easily be collected from the beds of small rills coming down the mountain side, and particularly along the line of partly washed out track going up from the Ten Mile to Mount Darwin. The fragments appear to be present at the rate of from one quarter to one half ounce per square foot of the rock rubble. If this proportion is maintained even approximately over the greater part of the area within which the Darwin Glass has been found, it is evident that in the aggregate this material would amount to probably several hundreds of tons.

A further test of Conder's theory would be the probable local enrichment in Darwin Glass near to, and just below, the assumed contours of the old ice cap, for this zone would have received the dumpings from the large area of Mount Darwin between the 1300 foot level and its summit, 3340 feet above sea level. Near Crotty, about five miles north of the Ten Mile, i.e., fifteen miles north of Kelly's Basin, the Darwin Glass is found reposing on a surface of Silurian limestone. This fact weakens the argument that the glass is of fulguritic origin, for obviously the fusion of the limestone would not produce a glass of a chemical composition like that of the Darwin Glass, which has from $88\frac{1}{2}\%$ to nearly 90% silica. In the letter by Twelvetrees to Professor Suess, the former states that " they (the mysterious pieces) have been found on the east side of Mount Darwin and at a third locality to the south of it, one and a half miles inland from Macquarie Harbour. At the last-mentioned place they were found in gravel under the grass." Possibly Twelvetrees is here referring to the occurrence three miles west of Mount Sorell, but this is nearly six miles inland from the eastern shore of Macquarie Harbour. Obviously much yet remains to be done in the way of delineating correctly the limits horizontally and vertically of the Darwin Glass, and particularly the relations of its occurrence to the gravel sheets between Strahan and Kelly's Basin, if the deposit extends as far westwards as this.

There can be little doubt but that these gravel traces are outwash apron gravels from some of the Pleistocene ice sheets. So far no traces of Darwin Glass have been met with in the oldest and earliest Pleistocene morainic deposits.

IV.—Form and Surface.

The larger fragments are rarely found in an absolutely unbroken condition. If, as supposed before, they are of meteoritic origin, and the fall dates back to Pleistocene time, they must have been subjected to frost weathering, as well as water erosion, and these two factors would certainly have largely contributed to splintering the glass. Occasionally, however, one finds a perfectly

unbroken specimen, particularly among the smaller examples. These latter are frequently of the tear-drop type. Between their two extremities these drops are generally curved. In the longer ones a small shelf or flange is developed on the concave side of this curve. Stalactitic forms often showing a spiral twist, are very common. These have a longitudinally striated appearance, something like that of pulled out and twisted toffee, owing to the considerable elongation of the gas pores parallel to the principal axis of the stalactite. Some of these types show a spiral twist of over 90°. Frequently such stalactites are bent irregularly. Occasionally one sees one of these types formed of greenish-brown glass with a droplet of clear translucent green glass firmly adhering to it. In many cases groups of small drops are closely aggregated together in many forms. They were apparently extruded, probably by gas pressure, from the molten interior of a larger fragment. More rarely the fragments are disc-shaped slightly thinned towards the centre, the disc being flattened so as to resemble a very small biscuit. More rarely still fragments are met with approaching in shape a somewhat flattened sphere. Only in some cases among the many hundreds of specimens collected has one been found (in this case by our party last April) showing a definite, though only slightly developed, rim, analogous to the rim so characteristic of Australites. This specimen is figured, Plate XIII., Fig. 1.

V.—Physical Characteristics.

(a) *Specific Gravity.*

The specific gravity of the Darwin Glass is recorded by Loftus Hills (2) as ranging from 1·874 to 2·180, the variation being due to the number of vesicles present. One of us, G. A. Ampt, has made a careful determination of the specific gravity of the powder used in an analysis and records it as 2·296 at 14·2°C. Suess (1) also records two determinations by E. Ludwig of the specimens analysed by him. These are given as 2·2921 and 2·2845 with water at 4°C=1·0. The specific gravity varies very definitely with the silica percentage, as can be seen by the following table :—

		SiO_2		Sp. Gr.		Analyst.
No. 1	-	86·34	-	2·296	-	Ampt
No. 2	-	88·764	-	2·2921	-	Ludwig
No. 3	-	89·813	-	2·2845	-	Ludwig
Average	-	88·30	-	2·2909	-	———

(b) *Hardness.*

Loftus Hills records the hardness as being 7 on Mohs' Scale. In many cases the determination of hardness is impossible as the

material is too brittle owing to the number of vesicles. The more solid specimens tested were just scratched with difficulty by quartz, so that the hardness of these was slightly below 7.

(c) *Colour, Lustre and Transparency.*

The colour of the Darwin Glass varies considerably. Some forms are dark smoky green to almost black and only translucent in very thin fragments. Others are greyish green, fairly free from vesicles and translucent in fairly thick fragments. Occasional pieces are almost white in colour and somewhat resemble pumice owing to the extremely vesicular nature of the material. Other colours observed were grey, olivine green and yellowish green.

In thin sections all the glasses are quite transparent, but as noted above the dark coloured forms and also the whitish forms are practically opaque in thick fragments, and only translucent in thinner fragments.

The lustre of the specimens on the weathered surfaces is dull, but ranging from vitreous to dull on freshly broken surfaces. Polished surfaces show a high vitreous lustre.

(d) *Microscopic Structure.*

All the thin sections examined showed that the material consisted of light greyish to greenish transparent glass. Some specimens showed a number of minute black specks. Flow lines were present in some specimens and absent in others. The denser forms showed a moderate number of vesicles, most of which were approximately circular. Occasional vesicles drawn out parallel to the flow lines were observed. The whitish forms when sectioned were found to be quite glassy with very numerous vesicles. In polarized light no definite trace of devitrification was found.

(e) *Refractive Index.*

The refractive index of two specimens was determined by a Herbert Smith refractometer, using sodium light, the results being:—

No. 1.—1·486.
No. 2.—1·497.

In addition the specific refractivity (3) of the three specimens analysed of which the specific gravity was determined was calculated from the specific refractivity of the minerals in the norm, and from this the refractive index, with the following results:—

K (Specific Refractivity)		Density		Ref. Index.
No. 1	- 0·2065	-	2·295	- 1·474
No. 2	- 0·2088	-	2·2921	- 1·479
No. 3	- 0·2087	-	2·2845	- 1·477

(f) *Radio-activity.*

One specimen was ground up and tested by Mr. J. S. Rogers for radio-activity and a completely negative test was obtained.

(g) *Melting Point.*

The microscopic examination of the material showed that it was wholly glassy so that no definite melting point would exist. The apparatus at our disposal would not allow of even a moderately accurate determination of the temperature at which crystallization of the thoroughly fused material would commence, so that no tests have been made.

VI.—Chemical Composition.

L. Hills (2) and E. Suess (1) both record analyses by Dr. Ludwig of Darwin Glass. Two additional analyses have been made by one of us, G. A. Ampt, and the following is a description of the methods employed and precautions taken to ensure a high degree of accuracy.

The analyses were carried out on the general lines prescribed by Washington and Hillebrand with certain modifications demanded by the exigencies of the cases, or shown by past experience to possess advantages in rationale and technique.

The material submitted for analysis was, from the point of appearance alone, of two qualities: I. dull, smoky-grey, glassy fragments in abundant quantity, II. pale, greenish-grey, clear, glassy fragments of which somewhat less than four grammes were available. Both qualities contained large numbers of vesicles, and the determination of specific gravity in the massive state was regarded therefore as futile. The determination of the specific gravity in the finely powdered form was, however, made in the case of I. all precautions being taken to remove entangled air from the powder by gently boiling with water under reduced pressure, in the specific gravity bottle used for the determination.

The specific gravity of the powder, referred to water at $14 \cdot 2°C.$, was found to be $2 \cdot 296$.

The preparation of samples for analysis presented no difficulties whatever, since the glassy material shatters with the greatest ease. Moreover, the rapidity of attack of the usual reagents rendered it unnecessary to grind any portion to an impalpable powder. Crushing in a steel mortar was carried on only until the whole of the selected fragments had passed through a 90-mesh sieve.

As with all very siliceous rocks, fusion with sodium and potassium carbonates yielded nice clear melts, and in neither case did the colour of the solidified cake give any suggestion of the presence of manganese. The fused mass, after disintegration with hydrochloric acid, was evaporated to dryness on the water bath and then baked in an air oven at 130° C. for 1-2 hours. This procedure has been found to reduce the non-insolubilized

silica to a practical minimum of about 2 milligrammes. The successive evaporations recommended in the treatises on the subject, while they may reduce this amount still further, do not result in the dehydration of the whole of the silica, reliance being placed on the ammonia precipitation for the recovery of the small amounts of silica still remaining in solution. Considerable economy in time is thus effected without in any way sacrificing accuracy. The complete removal of the last traces of insolubilized silica from the evaporating basins is a matter of great difficulty; a visible film remains after the most painstaking efforts of wiping with pieces of damp filter paper. The extent of the loss thus involved was investigated subsequently, using a platinum basin from which this film could be removed chemically with hydrofluoric acid; the adhering silica amounted to slightly less than 1 milligramme ($=0.1\%$ on a 1 grm. sample). This refinement could be introduced with advantage in certain special cases and if facilities were available.

Metals of the H_2S group were absent from I and the test was therefore not applied in II.

The separation of the ammonia precipitate calls for the greatest care, for it is in this operation that so many things can go wrong. A fruitful source of error lies in the ammonia itself. Long storage in bottles leads to the solution from the glass of both silica and alumina, and quite frequently the ammonia in reagent bottles has absorbed sufficient carbon dioxide to carry down in this group some calcium as carbonate. The commercial ammonia is therefore redistilled and kept in a heavily waxed bottle for use in all high class work.

The tendency of magnesium to be partially precipitated in this group is greater than is usually appreciated, and herein lies the fundamental necessity for dissolving and re-precipitating this group. No separation of aluminium and iron from calcium and magnesium will be complete unless the ammonia precipitate has been dissolved and re-precipitated at least once.

Precipitates of aluminium and ferric hydroxides should always be washed with a 2% solution of ammonium nitrate to suppress the formation of colloidal solutions; even so, the recovery of "dissolved" alumina from the filtrates should be made as a matter of course, and is best carried out after concentration to small bulk.

The addition of filter paper pulp prior to the precipitation with ammonia confers advantages quite out of proportion with the simplicity of the operation. Though it increases the bulk of the already voluminous precipitate still further, the fibres impart to it a porosity which makes for easy filtration and washing, both of which operations are extremely tedious with the ordinary gelatinous precipitates produced by ammonia. The subsequent ignition of these " pulp " precipitates yields a light porous mass which dissolves with great readiness in the pyrosulphate fusion. This is in marked contrast with the slow attack of the hard gritty nodules obtained by the older method.

To prepare the pulp, a 9-cm. ashless filter paper is torn into small fragments and drenched with about 5 c.cs of strong hydrochloric acid in a small flask. After a few minutes, water is added and the mush violently shaken to separate the fibres. The pulp is then strained off on a Gooch crucible, and washed once or twice, when the pad is removed to the precipitation vessel and disintegrated with a stirring rod.

The author of this section, G. A. Ampt, has adopted the practice of co-precipitating both manganese and nickel with the usual Group IIIA elements by adding a little bromine water to the hot ammoniacal liquid. The use of ammonium persulphate for this purpose is generally admissible, and is equally effective, but where appreciable quantities of lime are present it may lead to the precipitation of some calcium sulphate. The manganese and nickel thus find their way into the ignited " mixed oxides," as Mn_3O_4 and Ni_3O_4, and may be determined in aliquots of the solution of the pyrosulphate melt, the manganese colorimetrically after oxidation with sodium bismuthate, and the nickel by the glyoxime method. Both methods are capable of great accuracy, and even unweighable amounts of these oxides are readily detected. As a rule, the solution of the pyrosulphate melt is made up to 250 c.cs and used in the following manner: (i.) 100 c.cs for determination of total iron by reduction with zinc sulphide emulsion and titration with standard permanganate (4); (ii.) the same aliquot used for the glyoxime test for nickel, (iii.) 50 c.cs for the determination of manganese by the bismuthate process, (iv.) 50 c.cs for the determination of phosphoric anhydride, (v.) 10 c.cs for the colorimetric determination of titanium dioxide.

Neither manganese nor nickel was detected in either sample of Darwin Glass; a perceptible, though very minute precipitate of the yellow phospho-molybdate was obtained from I, indicating the presence of a trace of P_2O_5, while in II the test gave an absolutely negative result.

Ammonium sulphide produced a slight precipitate in both filtrates from the ammonia group; it was found to be mainly sulphur with a little platinum sulphide (from the crucibles), but it contained no cobalt.

Lime was present in minute amount (0.05%) in I, but could not be detected in II. This is interesting, and probably significant, in view of the distribution of P_2O_5.

Total water was determined by heating half-gramme portions in a small furnace and collecting the vapour in weighed absorption tubes. Control tests were made both with pure sodium bicarbonate $(0.1$ grm.$)$ and with minute glass bulbs holding from 0.005 to 0.01 grm. of water, before the tests on the rock were undertaken. The weight of water collected, viz. I—0.46%, II—0.36%, showed remarkable agreement with the loss in weight suffered by the samples after correcting for oxidation of FeO to Fe_2O_3, viz. I—0.43%, II—0.33%.

The determination of ferrous oxide was made by dissolving the sample in a mixture of hydrofluoric and sulphuric acids, the apparatus employed resembling that advocated by Treadwell (5, p. 207). The platinum crucible was supported within a small leaden chamber through which carbon dioxide was circulated, and which was heated to 120°C. by immersion in an oil bath. Darwin Glass, obsidianites, and similar highly siliceous and homogeneous materials yield readily to HF, and it is not necessary to grind them to impalpable powders with the consequent danger of oxidizing some ferrous oxide.

The following method has been adopted for many years for the alkalies in preference to that of Lawrence Smith. The mineral is disintegrated in a platinum dish on a water bath with a mixture of alkali-free hydrofluoric and sulphuric acids, whereby the whole of the silica is expelled as volatile SiF_4. The solution is finally evaporated on a sand bath till fumes of SO_3 cease to be evolved and the residue is dry, but the heating should not be continued until the sulphates decompose, or sparingly soluble basic alums may be formed and alkalies lost. The sulphates after solution in water are treated with an excess of the purest solid barium hydroxide. This results in the complete precipitation of the sulphate radicle as $BaSO_4$ and of all the bases except calcium, the alkalies, and of course the excess barium, as hydroxides. The precipitate is filtered off and thoroughly washed (this is the only difficult operation in the process), and the filtrate is saturated with CO_2 and boiled down to small volume. Ba and Ca are thus thrown out as carbonates and are removed by filtration, while in the filtrate the alkalies are converted into chlorides and weighed. A few milligrammes of Ba invariably escape separation, and a series of small scale treatments with purest ammonium carbonate, filtrations and evaporations must be undertaken until the weight of the alkali chlorides is constant. It has never been found necessary to do this more than twice.

Potassium is separated as the platinichloride according to the usual procedure, but the final evaporation is made in a porcelain crucible with the addition of a little aqua regia to reoxidize any platinochloride formed by filtering the platinichloride through paper. The alcoholic filtrate containing the sodium platinichloride may be examined for lithium by means of the spectroscope.

The search for zirconium is now never omitted and is conveniently made on the same sample used for the detection of barium and sulphur. The determination as basic zirconium phosphate is somewhat tedious on account of the tendency of this salt to carry down others from which it must be purified by re-treatment. The presence of zirconia in sample II could not be definitely established, but barium, and sulphur in all forms, were absent from both specimens.

Owing to lack of material, further tests on II had to be abandoned. No. I was examined for carbonate in a miniature baryta-vacuum apparatus capable of detecting less than half a milli--

gramme of CO_2 (6, p. 251)—none was found. The examination for chlorides was unsatisfactory and inconclusive. Owing to the inability to obtain chlorine-free sodium carbonate, a blank test yielded an amount of chlorine many times greater than that which it should be possible to detect. If present, however, the amount would not exceed 0·05%.

The complete analyses together with those of Ludwig are given in the following table :—

Analyst	Ampt		Ludwig	
	I.	II.	III.	IV.
Appearance	Smoke grey, full of vesicles	Pale greenish grey, many vesicles	Olivine green	Dirty white
SiO_2 -	86·34	87·00	88·764	89·813
Al_2O_3 -	7·82	8·00	6·127	6·207
Fe_2O_3 -	0·63	0·19	——	0·258
FeO -	2·08	1·93	1·238	0·895
MnO -	nil	nil	tr.	tr.
MgO -	0·92	0·82	0·575	0·727
CaO -	0·05	nil	0·174	——
Na_2O -	0·15	0·14	0·129	0·010
K_2O -	0·87	0·99	1·363	1·054
H_2O + -	0·43	0·36	——	——
H_2O — -	0·03			
CO_2 -	nil	nil	——	——
TiO_2 -	0·52	0·51	1·240	0·867
P_2O_5 -	tr.	nil.	——	——
ZrO_2 -	0·11	tr. (?)	——	——
Cr_2O_3 -	nil	nil	——	——
NiO, CoO -	nil	nil	——	——
BaO, SrO -	nil	nil	——	——
SO_3 -	nil	nil	——	——
Cl -	nil (?)	nil (?)	——	——
	99·95	99·94	99·610	99·821
Sp. Gr.	2·296	——	2·921	2·845

These four analyses have been classified according to the Quantitative Classification with the following results. The analyses are given in the same order as before.

			I.	II.	III.	IV.
Quartz	-	-	79·80	80·28	81·24	84·78
Orthoclase	-	-	5·00	5·56	8·34	6·12
Albite	-	-	1·05	1·05	1·05	——
Anorthite	-	-	0·28	——	·83	——
Corundum	-	-	6·53	6·73	4·08	5·10
Hypersthene	-	-	4·43	4·61	1·76	1·80
Magnetite	-	-	0·93	0·23	——	0·46
Ilmenite	-	-	1·06	0·91	2·28	1·67

All the analyses fall into Class 1 Persalane and Order 1 Per-
quaric. Rangs and sub-rangs are not considered necessary in this
group. Only three analyses are quoted by Washington (7) in
Class 1 Order 1.

VII.—Correlation with kindred Bodies, such as Moldav-
ites, Australites, Billitonites, Schonite.

It has been shown by one of the authors (8) that all the other
forms of Tektites of which analyses have been made fall into
rangs and sub-rangs in the Quantitative Classification in which
very few examples of normal igneous rocks are found. This is
now shown to be equally true in respect to the Darwin Glass, so
that rocks having compositions at all comparable with those of
the Tektites are extremely rare among the igneous rocks of the
earth's surface. At the same time, however, the strong similarity
in composition of the various Tektites to one another is well
shown by their relative positions in the Quantitative Classifica-
tion.

The analyses of Australites, Billitonites and Moldavites have
been compared by one of us (9) by means of variation diagrams.
Suess (1) has also used a somewhat different form of variation
diagram which includes in addition Ludwig's two analyses of
Darwin Glass (Queenstownite). Variation diagrams are usually
compiled either from the percentages of oxides as given by the
analyses or from the molecular ratios determined from these per-
centages. The second form is that used by Suess. The summa-
tions of analyses and the percentages of water present vary. In
some cases TiO_2 is not determined and in other cases the ferrous
and ferric oxides have not been separated. If the molecular
ratios are determined the totals for different analyses will vary
greatly, so that in either case the analyses are not strictly com-
parable.

The molecular ratios give a better conception of the relative
proportions of the oxides than do their percentages by weight.
In order to obtain more satisfactory graphing, the molecular
ratios of the various types have been determined from the
analyses and then reduced to percentages. The water, both com-
bined and hygroscopic, has been omitted and the TiO_2 reduced to
Ti_2O_3. This latter is quite open to question, but the amount of
titanium is small and the effect is practically negligible. The re-
duced analyses are given in the following table:—

	Australite Uralla N. S. Wales *	Australite Uralla N. S. Wales †	Australite Uralla N. S. Wales	Billitonite Tebrung Dendang	Australite Upper Weld Tasmania	Australite Bet. Everard Range & Fraser Range S. Aust.	Billitonite Lura No. 13 Dendang
	I.	II.	III.	IV.	V.	VI.	VII.
SiO_2	70·8	71·1	74·1	74·5	74·9	75·4	75·9
Ti_2O_3	—	—	0·1	—	0·3	—	—
Al_2O_3	10·8	10·9	9·7	7·6	9·4	8·5	7·5
Fe_2O_3	0·3	0·3	0·2	0·4	0·2	0·3	—
FeO	6·0	6·1	4·5	4·9	4·4	5·0	5·1
MgO	4·3	4·3	4·0	4·1	4·0	3·8	3·8
CaO	4·5	4·5	4·5	4·3	3·7	4·0	3·3
Na_2O	1·3	—	1·2	2·5	1·4	1·5	2·5
K_2O	2·0	2·8	1·7	1·7	1·7	1·5	1·9
Total	100·0	100·0	100·0	100·0	100·0	100·0	100·0

	Australite Coolgardie W. Aust.	Australite Kalgoorlie W. Aust.	Australite Mt. Elephant Victoria	Australite Pieman Tasmania	Australite Hamilton Victoria	Australite Peake Statn. S. Aust.	Moldavite Trebilsch Bohemia
	VIII.	IX.	X.	XI.	XII.	XIII.	XIV.
SiO_2	76·0	77·0	77·5	78·6	81·3	82·0	82·2
Ti_2O_3	0·4	—	0·3	0·3	0·3	0·4	—
Al_2O_3	8·5	7·5	8·3	7·8	7·1	6·2	7·6
Fe_2O_3	0·3	0·4	0·2	0·1	0·1	0·1	0·1
FeO	4·4	4·7	4·1	3·5	3·5	3·3	3·2
MgO	3·9	3·4	3·0	2·9	2·3	2·5	2·3
CaO	3·6	3·5	3·7	4·3	2·9	2·7	2·2
Na_2O	1·4	1·8	1·6	1·1	1·3	1·4	0·6
K_2O	1·5	1·7	1·3	1·4	1·2	1·4	1·8
Total	100·0	100·0	100·0	100·0	100·0	100·0	100·0

* Iron and alkalies recalculated to accord with other specimens from Uralla.
† Iron recalculated to accord with other specimens from Uralla.

	Moldavite Skrey in Dukovan Mähren	Moldavite Trebilsch Bohemia	Moldavite Radomiltz Bohemia	Moldavite Radomiltz Bohemia	Australite Curdies' Inlet Victoria	Moldavite Budweis Bohemia	Moldavite Radomiltz Bohemia
	XV.	XVI.	XVII.	XVIII.	XIX.	XX.	XXI.
SiO_2	82·7	83·0	82·5	83·8	84·4	86·2	86·3
Ti_2O_3	0 6	—	—	—	0·2	—	—
Al_2O_3	7·3	7·5	8 1	8·1	6·6	5·9	6·2
Fe_2O_3	—	0·1	—	0·8	0·3	—	—
FeO	2·4	2·9	2·3	1·3	2·8	1·1	1·7
MgO	2·5	2·2	0·4	1·9	2·2	2·4	1·6
CaO	1·5	1·8	3·6	1·4	1·7	2·3	2·5
Na_2O	0·7	0·4	0·3	0·8	1·0	0·6	0·3
K_2O	2·2	2·1	1·8	1·9	·8	1·5	1·4
Total	100·0	100·0	100·0	100·0	100·0	100·0	100·0

	Darwin Glass Tasmania (Ampt)	Darwin Glass Tasmania (Ampt)	Darwin Glass Tasmania (Ludwig)	Darwin Glass Tasmania (Ludwig)	
	XXII.	XXIII.	XXIV.	XXV.	
SiO_2	90·7	91·1	92·5	93·2	
Ti_2O_3	0·2	0·2	0·5	0·3	
Al_2O_3	4·8	4·9	3·8	3·8	
Fe_2O_3	0·3	0·1	——	0·1	
FeO	1·8	1·6	1·1	0·8	
MgO	1·4	1·3	0·9	1·1	
CaO	0·1	0·0	0·2	0·0	
Na_2O	0·1	0·1	0·1	0·0	
K_2O	0·6	0·7	0·9	0·7	
Total	100·0	100 0	100·0	100·0	

The percentages of molecular ratios have been graphed. In text-figure 2 the sums of the R_2O_3, RO and R_2O oxides are shown and for comparison those of some average compositions of the common more acid plutonic rocks are also given. Undoubtedly it would have been preferable to use average volcanic rocks rather than plutonic but up to the present similar averages of analyses of volcanic rocks have not been worked out.

In testing Daly's (10) averages for granites, quartz-monzonites, granodiorites, quartz-diorites, diorites, gabbros and norites by means of variation diagrams it was found that the various points for the percentages of the molecular ratios of the R_2O_3, RO and R_2O molecules fell practically on straight lines. Following this up all the better analyses of the above mentioned rocks quoted by Washington (7) were reduced to percentages of molecular ratios and graphed. Some analyses showed considerable deviation from the general average and were rejected as being probably not true to name. A series of averages was then calculated and the averages of the more acid types are shown on the diagram by crosses.

In text-figure 3 the graphs of the percentage molecular ratios of the individual oxides of the Tektites are given.

These variation diagrams strongly support the contention that the Tektites are all genetically related to one another and clearly show the close relationship in composition of the Darwin Glass to the remaining forms.

A comparison of the graphs for the Tektites with those for the common acid plutonic rocks shows that the two series are quite distinct in composition.

VIII.—Distribution of Tektites on the same Great Circle.

What is probably an extremely significant fact about Darwin Glass, in common with other Tektites, is that they all lie approximately on the same great circle.
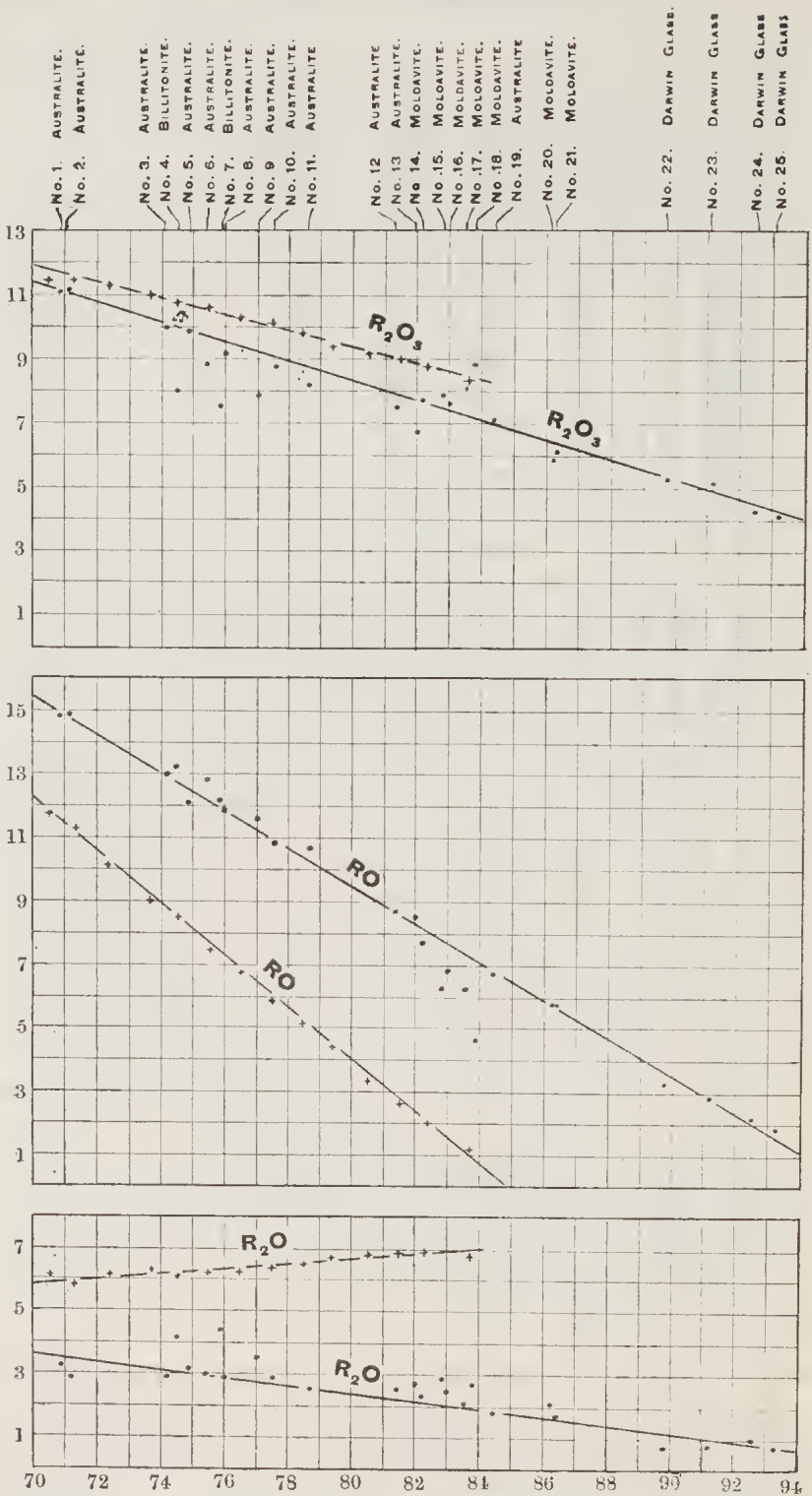
10

FIG. 2.—GRAPHS OF SUMS OF R_2O_3, RO AND R_2O OXIDES IN TEKTITES.
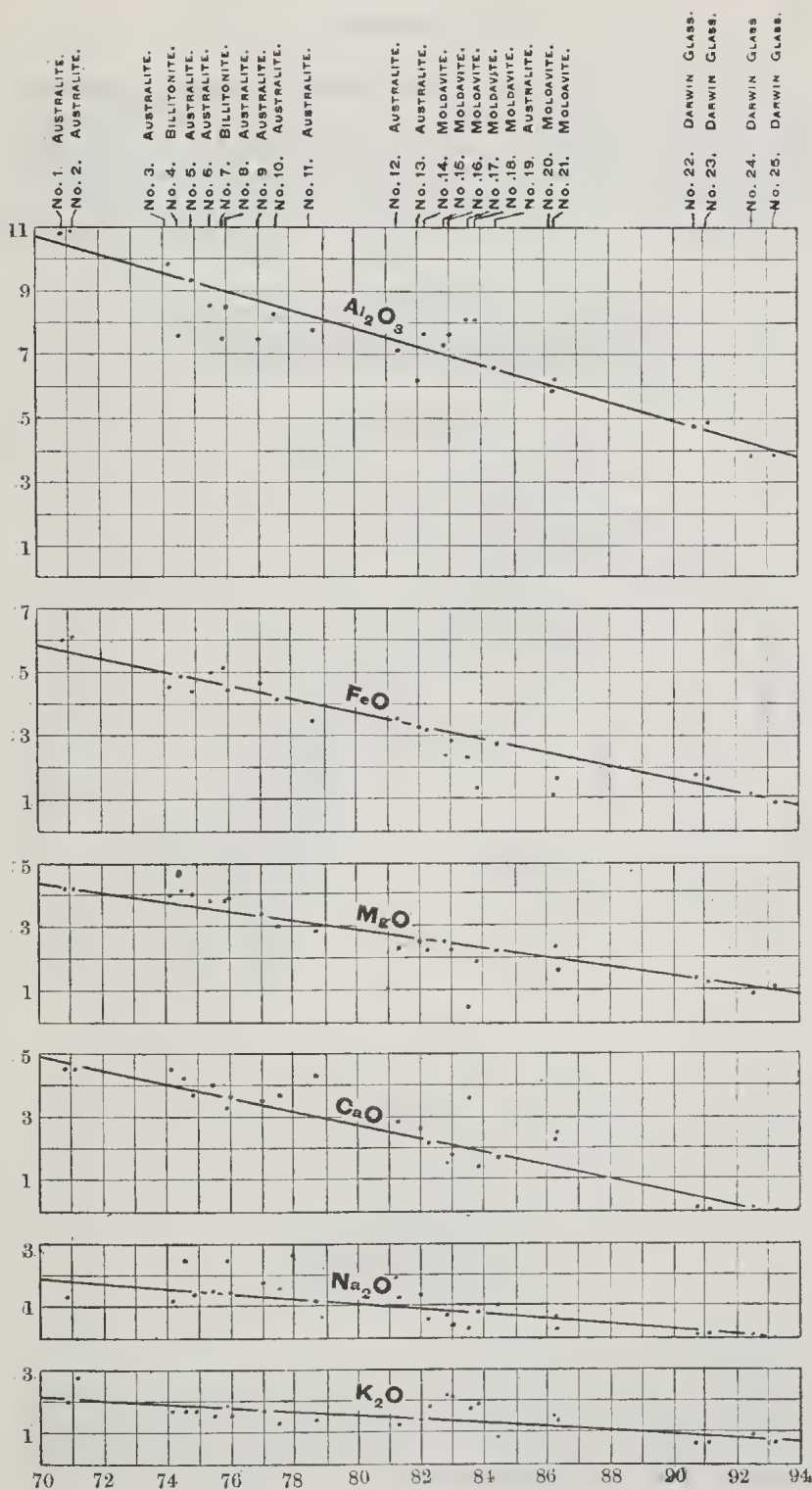
Fig. 3—Graphs of percentage molecular ratios of individual oxides in the Tektites.

If Tasmania be taken first it has Darwin Glass very plentifully,. but also very locally, distributed, over a region in the south-west, upon and around Mount Darwin.   No Australites, so far, have· been found in this part of the island.   Further north Australites: occur, frequently several together in one group.   The shower of Australites spread over Victoria, New South Wales, the southern·

Map on Stereographic Projection
showing Great Circle ∿₂₀· with belt on each side of it
10° wide, indicating that all the known tektites of
the World lie approximately on the same Great Circle.

NORTH POLE

GREAT CIRCLE

W.   EQUATOR   E.

SOUTH POLE

A. *Schonit of Sweden*
B. *Moldavites of Moldau River, etc.*
C. *Billitonites of Banca, Billiton and S. Borneo.*
D. *Australites of Australia.*
E. *Darwin Glass and Australites of Tasmania.*

Fig. 4.

extremity of Queensland, South Australia, and Central Australia,. to beyond Charlotte Waters, and as far north west as the Tanami goldfield, Western Australia, where they appear to be specially abundant in the neighbourhood of the Coolgardie-Kalgoorlie gold-

field. Northwards they have been traced to about half way be-
tween Wiluna and Hall's Creek on the Canning Stock Route.
They have also been found a few miles inland from the coast
near Wallal. They are thus strung out over an area about 2000
miles in length, from about E.40°S. to W.40°N. If this bearing
be now followed on a great circle, it leads to Java, the south-east-
ern portion of Borneo, Banca and Billiton where the kindred
bodies, Billitonites, occur somewhat plentifully. Following the
same great circle, one finds, after a long interval, that one reaches
Moldavia, where, of course, the closest allies of Darwin Glass,
Moldavites, are very abundant and somewhat widely distributed.
Again, on the same great circle, we find an isolated occurrence,
in Scandinavia, of Schonite. In view of this remarkable distri-
bution, there would seem to be a high probability that all these
five bodies of Tektites belong to one and the same group of
meteorites. They seem to have been either discrete swarms of
small meteorites, or represent the scorification products of sepa-
rate, larger bodies, which became, to a great extent, disrupted
probably in their passage through the Earth's atmosphere. The
distribution of the ultra-acid glasses, Moldavite and Darwin
Glass, at the two extremities of the belt occupied by the Tektites
(with the solitary exception of the Schonite) suggests an original
gravitational separation of the meteoritic swarm into more
siliceous portions on the periphery, and more basic types towards
the centre. Though one is not sure of the sense of the move-
ment, it may be assumed that as the swarm approached the earth,
it became so greatly elongated towards the earth that the ring of
acid meteorites was more or less disrupted into a vanguard and
rearguard. The vanguard arrived in Tasmania, the main body
fell over Northern Tasmania, Australia, and the Netherlands
East Indies, and the rearguard, separated by a considerable dis-
tance, fell in Moldavia.

IX.—Hypotheses as to Origin.

Hypotheses as to the origin of the Tektites other than Darwin
Glass have been discussed at length by many authors (see biblio-
graphic lists by Suess (1) and Summers (8). The origin of the
Darwin Glass has also been discussed by Suess and Loftus Hills
(2). The hypotheses may be summarised as follows:—

(a) *Artificial.*

As recorded by Loftus Hills, this glass was not at first recog-
nized as something unique owing to the material being found in
the vicinity of copper smelting works at Crotty. Thus the glass
was presumed to be simply a furnace slag. The analyses of
course disprove this and the mode of occurrence and distribution
also show that such an origin is impossible, as white men had
only penetrated the area for about seventeen years at the time of

the first discovery of Darwin Glass and the area had never been settled. The Tasmanian aborigines cannot be seriously considered as a factor in the distribution of a substance which does not occur naturally as a volcanic product and which they were incapable of producing artificially.

(b) *Volcanic.*

The Darwin Glass is certainly not earlier than the late Tertiary period. The principal volcanic rocks of this period in Tasmania and Victoria were basalts with occasional andesites and trachytes. The undevitrified nature of the glass precludes the possibility of this material being derived from any pre-Tertiary glassy igneous rocks. Therefore the only volcanic sources to which this material could be ascribed produced either basic or intermediate volcanic rocks only. The silica percentage in the Darwin Glass, approximately 88%, makes it even more difficult than in the case of the Australites, silica percentage 65 to 76, to suggest a local volcanic source. So far those holding the view that Australites are of volcanic origin have failed to suggest an Australian source which can be reasonably accepted. This led to the suggestion that the possible source was New Zealand or the East Indies. No rocks from these areas have been shown to be comparable in composition with the Australites, although some show a sufficiently high silica percentage. Even granting the possibility that the volcanoes from these areas might have produced material of the requisite composition, the transport of the material over such great distances cannot be ascribed to normal volcanic agencies. E. J. Dunn (11, 12, 13) has postulated the bubble hypothesis for the transport of Australites but it seems quite impracticable to extend this idea to cover the case of the Darwin Glass, even if it were accepted as a possible explanation of the distribution of Australites. If we are to believe that the Darwin Glass is of volcanic origin we must also believe that there exists in the neighbourhood a volcano which produced the glass.

If we consider the composition of the Darwin Glass we find that the hypothetical volcano would be required to produce a unique volcanic glass. The highest percentage of silica in an obsidian recorded by Washington is Dunn's so-called marekanite from New Zealand, with approximately 77% SiO_2. The Darwin Glass averages approximately 88% SiO_2. Richards (14) records an analysis of a rhyolite from Blackall Ranges, Queensland, with 85·13% SiO_2, and also quotes examples of other highly siliceous rocks. In all these cases, however, evidence of secondary silicification is noted and the compositions as given do not represent the original compositions at the time of extrusion. In the case of the Darwin Glass, if secondary silicification were accepted as a possible explanation of the high silica percentage, it would be necessary to assume that subsequently refusion of the material had taken place, to account for the absence of devitrification and

absence of evidence of the presence of secondary silica. Taking into account the absence in the neighbourhood of evidence of contemporary volcanoes producing even normal acid rocks, and also the abnormal composition of the Darwin Glass, we have no hesitation in rejecting the hypothesis of a volcanic origin for these Tektites.

(c) *Fulguritic.*

(i.) *From fusion of siliceous sands at surface of ground.*

The records of the occurrence of fulgurites are comparatively few, and the plentiful distribution of the Darwin Glass has no parallel in such records. An examination of a fulgurite from New South Wales presented to us by Mr. Card shows that an open tube about 3/16″ in diameter runs throughout the specimen. Surrounding this tube the material is for the most part quite glassy but towards the margin the vitreous appearance is lost and this portion consists of only partially fused material. This is confirmed by an examination of a cross section of the fulgurite under the microscope. The central area is glassy but the outer portion affects polarized light and similates incipient devitrification. This appearance is, however, probably due to incomplete fusion of the original particles rather than to subsequent alteration from an isotropic glass.

This specimen of course cannot be taken as being typical of all fulgurites but shows that in this case there is very marked dissimilarity between the fulgurite and the Darwin Glass. According to Loftus Hills the Tektites are found lying directly on limestone in soil wholly composed of peat and the residuum from the decomposition of the limestone, and also in other places resting directly on quartzite. Since, as pointed out by Loftus Hills, a fulgurite must necessarily correspond approximately in composition with the surrounding material of which it is a fused portion, it is inconceivable that fulgurites of similar composition and appearance could be formed under such different conditions. The evidence therefore is distinctly against a fulguritic origin for the Darwin Glass.

(ii.) *From fusion of dust clouds in a thunderstorm.*

Fusion of dust clouds by lightning discharge has been suggested as a possible explanation of the formation of Australites. This idea while suggesting a possible source of the Australite does not explain their distribution or similarity in composition. This hypothesis postulates an exceptionally dense dust cloud and the production from this by means of lightning discharge of moderate sized pieces of a perfectly fused glass, a phenomenon which has never been recorded in any part of the world. A large proportion of the Australites are found in places in which dense clouds are by no means uncommon but the Darwin Glass is only found in an area, at the present time of heavy rainfall, and in which dust storms similar to those of Central Australia are im-

possible. There is no evidence to show that arid conditions existed in this area during Pleistocene times, but rather the reverse, as it has been shown earlier that the Darwin Glass was probably contemporaneous with the Pleistocene glaciation of Western Tasmania. Should such a fusion of dust take place one would expect the product obtained to be more related to the fulgurites than to a perfectly homogeneous glass, i.e., the mass would consist of fused material together with a considerable amount of only partially fused dust particles. No evidence of such fritted material has been seen.
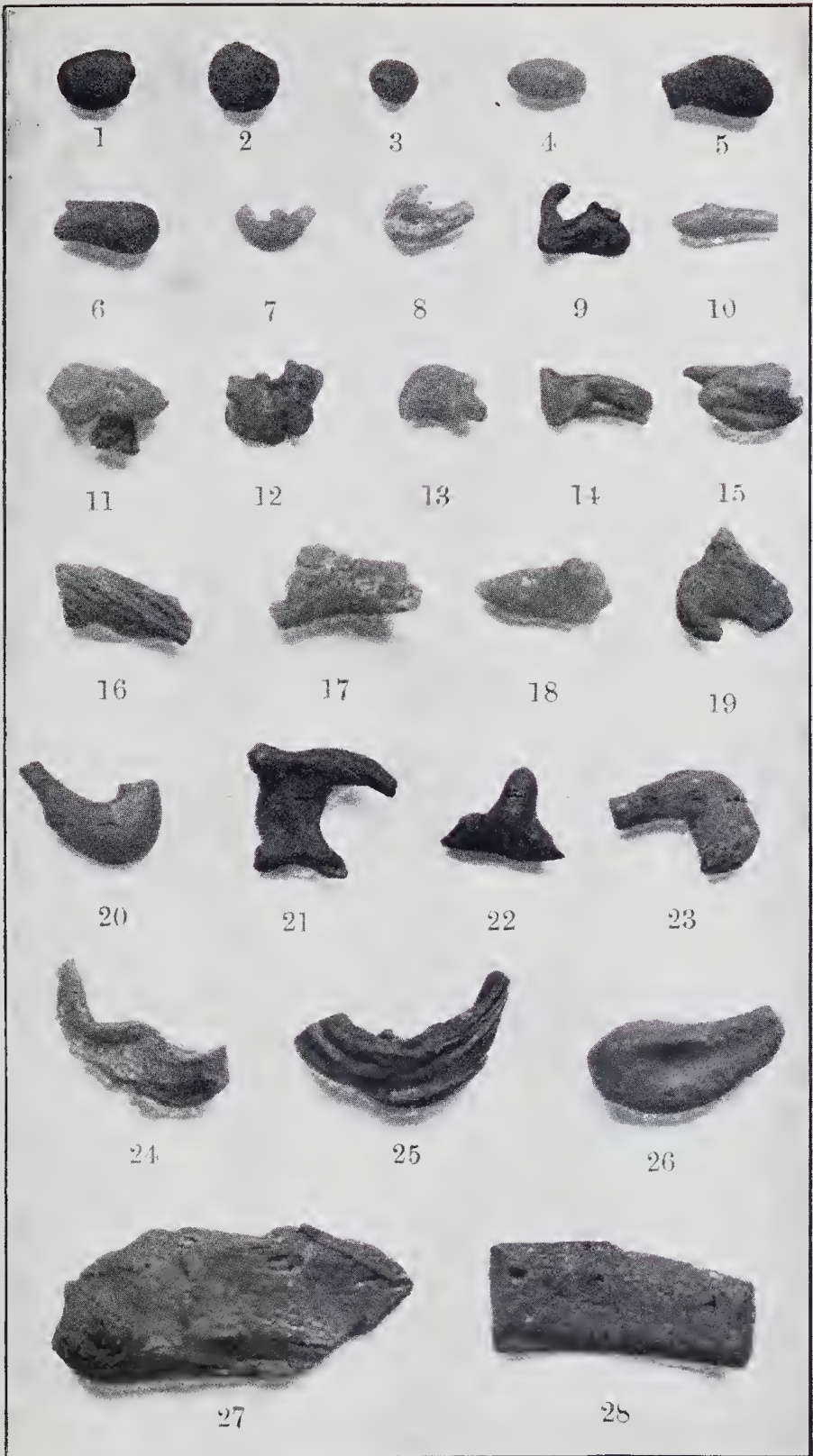
(d) *Meteoritic.*

As other hypotheses have failed to account for the composition, form and distribution of the Darwin Glass, the meteoritic origin of this material must be considered. The majority of those who have seriously investigated the origin of the earlier known tektites are convinced that they are of extra-terrestrial origin. The composition and mode of occurrence show that the Darwin Glass is closely related to the Moldavites, Australites and Billitonites and we infer that they had a common mode of origin. Unfortunately no positive evidence of a meteoritic origin of the Tektites has been found and such evidence could only be obtained by the actual observation of a similar shower in the future. On the other hand no unanswerable arguments have been advanced against this hypothesis as being able to explain the source, form, composition and distribution of the Tektites.

Conditions must have been somewhat different in the different areas as the forms vary greatly. All are isotropic glass, so that they must have cooled rapidly from a molten state. In the case of the Australites, the characteristic forms are believed to be due to rotation of liquid bodies modified by the resistance of the atmosphere.

A similar explanation of the forms of the Moldavites is not possible, as they are quite irregular and the characteristic forms of the Australites seem to be entirely absent. The fusion surfaces on certain Moldavites described by Weinschenk (15) suggest that only partial fusion of these bodies took place during their flight through the atmosphere.

This explanation would assume that the Moldavites were glassy bodies before entering the earth's atmosphere. Alternatively the Moldavites may represent fragments of some larger body or bodies which exploded fairly close to the earth's surface and consequently the fragments had not sufficient time to assume the forms developed by rotating fluids. Some portions may have had their flight sufficiently checked by the explosion to solidify and partial refusion of the surface may have been due to their subsequent reacceleration under the action of gravity.

In the case of the Darwin Glasses their fragmental nature is apparent and is most satisfactorily explained as the result of the

Darwin Glass, Tasmania.